

# Heavy flavour production in high-energy $ep$ collisions

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A selection of recent results on heavy quark production at the HERA collider by the H1 and ZEUS collaborations are presented with a focus on charmonium production in DIS, charm fragmentation and beauty production.

## 1. Introduction

In the heavy quark production processes there is at least one hard scale and hence perturbative QCD calculations are expected to be reliable. At HERA, where electrons or positrons of 27.5 GeV are collided with protons of 920 GeV (820 GeV before year 1998), pQCD predictions are tested in  $ep$  interactions. The HERA collider is a unique facility to investigate the parton dynamics, the heavy quark production and fragmentation properties and other topics.

The main kinematic variables are the virtuality of the exchanged photon,  $Q^2$ , the photon–proton centre-of-mass energy,  $W$ , the Bjorken scaling variable,  $x$ , and another scaling variable,  $y$ , which is the energy fraction of the lepton beam transferred to the exchanged photon.

Both the photoproduction ( $Q^2 < 1 \text{ GeV}^2$ ) and deep inelastic scattering (DIS,  $Q^2 \gtrsim 1 \text{ GeV}^2$ ) regimes are studied.

## 2. Inelastic $J/\psi$ production

In Fig. 1 recent results on the inelastic  $J/\psi$  production in DIS regime measured by ZEUS [1] are compared to different theoretical predictions including colour singlet (CS) and colour octet (CO) contributions as well as the CS contributions only. Neither shapes nor normalisation are described if CO contributions are included whereas CS contributions alone generally agree with the data. This is also true for the properties of the hadronic fi-

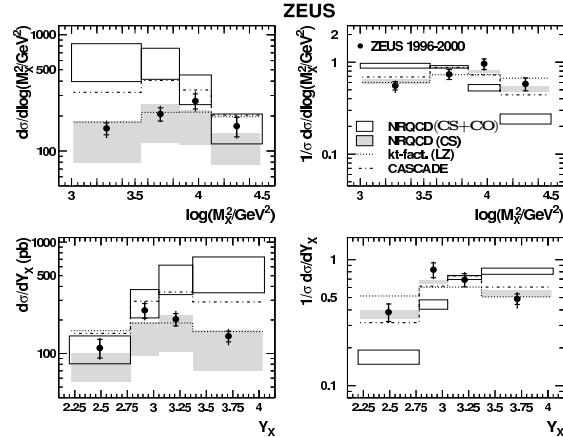


Figure 1. Absolute and normalised differential cross sections for the reaction  $ep \rightarrow eJ/\psi X$  in the kinematic region  $2 < Q^2 < 80 \text{ GeV}^2$ ,  $50 < W < 250 \text{ GeV}$ ,  $0.2 < z < 0.9$  and  $-1.6 < Y_{\text{lab}} < 1.3$  as a function of  $\log(M_X^2)$  and  $Y_X$ . The data are compared to LO NRQCD (CS+CO) predictions, a LO NRQCD (CS) calculation, a prediction in the  $k_T$ -factorisation approach within the CSM and the CASCADE (CCFM-based) MC predictions.

nal state (invariant mass,  $M_X$ , and rapidity,  $Y_X$ ) which were measured in this process for the first time. From similar studies in photoproduction [2] it is known that resummation techniques for soft gluon emission can improve the theoretical description, however such calculations are not available in DIS. CASCADE Monte Carlo predictions are above the data but the shapes are well described. A calculation in the  $k_T$ -factorisation approach based on BFKL evolution equations gives the best description of the data.

\*Supported by the Russian Federal Agency for Science and Innovations and DESY.

### 3. Charm fragmentation

Fragmentation ratios and fractions in photoproduction has been analysed by H1 [3] and ZEUS [4]. In this analysis the charm ground states,  $D^0$ ,  $D^+$ ,  $D_s^+$ ,  $\Lambda_c^+$ , and the charm vector meson  $D^{*+}$  were measured. As an example in Fig. 2 the three-track invariant mass  $M(Kp\pi)$  distribution is shown for the  $\Lambda_c^+/\bar{\Lambda}_c^-$  candidates after subtraction of reflections from  $D^+$  and  $D_s^+$  decays. In charm fragmentation, the ratio of neutral to charged D-meson rates,  $R_{u/d} = (cu)/(cd) = 1.100 \pm 0.078$ (stat.), is consistent with the isospin invariance, the strangeness-suppression factor is  $\gamma_s = (2cs)/(cd + cu) = 0.257 \pm 0.024$ (stat.) and the fraction of charged D mesons produced in a vector state is  $P_V^d = 0.566 \pm 0.025$ (stat.) which is not consistent with the naive spin counting [4]. The fragmentation fractions,  $f(c \rightarrow D, \Lambda_c)$ , were also measured [4]:  $0.217 \pm 0.014$  for  $D^+$ ,  $0.523 \pm 0.021$  for  $D^0$ ,  $0.095 \pm 0.008$  for  $D_s^+$ ,  $0.144 \pm 0.022$  for  $\Lambda_c^+$  and  $0.200 \pm 0.009$  for  $D^{*+}$ <sup>2</sup>. These values are consistent with H1 results [3]. Also they are in general agreement and have precision competitive with the combined  $e^+e^-$  data [5] thus supporting the universality of  $c$ -fragmentation.

A study of the charm fragmentation function have been done by H1 in DIS [6] ( $2 < Q^2 < 100$  GeV $^2$ ,  $0.05 < y < 0.7$ ). In the definition of the fractional transfer of the  $c$  quark energy to a  $D^*$  meson ( $D^* \rightarrow K\pi\pi_s$ ,  $p_T > 1.5$  GeV,  $|\eta| < 1.5$ ) the  $c$  quark energy was approximated by the energy in the appropriately defined hemisphere associated to the  $D^*$  in the  $\gamma^*p$  frame:  $z_{hem} = (E + p_L)_{D^*} / \sum_{hem}(E + p_L)$ . This was done to establish a close analogy to the measurements in  $e^+e^-$  experiments. The distribution over  $z$  is in agreement with recent  $e^+e^-$  annihilation data from CLEO at a similar centre-of-mass energy of the  $c\bar{c}$  pair. The data are well described by RAPGAP Monte Carlo where either Peterson or Kartvelishvili parametrisation of the fragmentation function was implemented. The best description was achieved with  $\varepsilon = 0.018^{+0.004}_{-0.004}$  (Peterson) or  $\alpha = 5.9^{+0.9}_{-0.6}$  (Kartvelishvili). The  $\varepsilon$

<sup>2</sup>Only statistical errors are shown for the fragmentation ratios and fractions; all others are omitted.

value is lower than the previous ZEUS photoproduction result  $\varepsilon = 0.064 \pm 0.006^{+0.011}_{-0.008}$  [7].

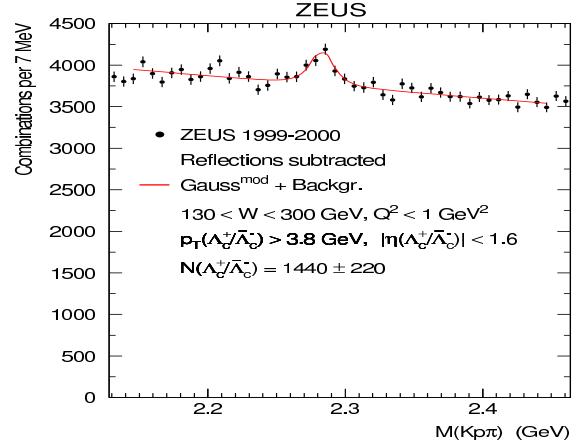


Figure 2. The  $M(Kp\pi)$  distribution for the  $\Lambda_c^+/\bar{\Lambda}_c^-$  candidates in photoproduction.

### 4. Charm with jets

Heavy quark production in association with jets measured recently by H1 [8] and ZEUS [9] provides a test of a multiscale process. The ZEUS measurement of jet cross sections in charm photoproduction ( $Q^2 < 1$  GeV $^2$ ,  $130 < W < 280$  GeV) has been confronted with both massive and massless calculations. In the so-called massive scheme there are three active quark flavours in the proton or photon with heavy quarks produced dynamically via e.g. boson gluon fusion. The approach is expected to be valid at low transverse momenta of the  $c$  quark. In the resummed massless scheme there are up to five active partons and it is valid at high transverse momenta. Combined calculation schemes (like variable flavour number scheme) also exist.

The  $D^*$  mesons ( $D^* \rightarrow K\pi\pi_s$ ) were required to be in the kinematic region  $p_T > 3$  GeV,  $|\eta| < 1.5$ . Jets ( $k_T$  cluster algorithm) with  $-1.5 < \eta^{\text{jet}} < 2.4$ ,  $E_T^{\text{jet}} > 6$  GeV were selected. For the dijet analysis the highest  $E_T^{\text{jet}}$  jet was required in addition to satisfy  $E_T^{\text{jet}} > 7$  GeV.

For all  $E_T^{\text{jet}}$  and  $\eta^{\text{jet}}$  the shapes of inclusive jet cross sections with and without a  $D^*$  tag are well described by both theoretical predictions whereas

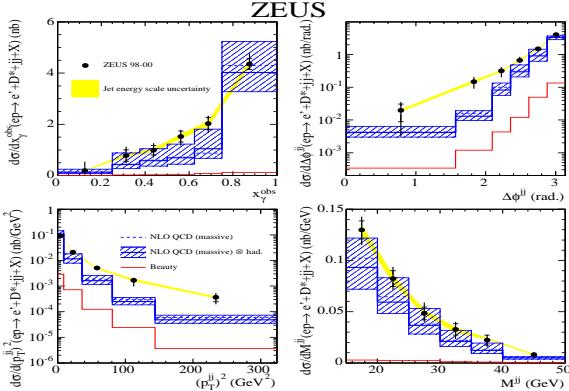


Figure 3. Dijet correlations in charm photoproduction compared to massive NLO QCD predictions. The beauty component in the data (HERWIG MC estimate) is also shown.

the normalisation is described by their upper limits. There is no excess in the forward region (positive  $\eta^{\text{jet}}$ ) observed previously in the purely inclusive jet measurements. In Fig. 3 dijet correlations are shown in comparison to the massive NLO QCD predictions: the fraction of the photon momentum participating in the dijet production,  $x_\gamma^{\text{obs}}$ ; the azimuthal separation of the jets,  $\Delta\phi^{jj}$ ; the transverse momentum squared of the jets,  $(p_T^{jj})^2$ ; and the dijet invariant mass,  $M^{jj}$ . The dijet correlations are directly sensitive to the higher order corrections as for the lowest order  $2 \rightarrow 2$  process  $\Delta\phi^{jj} = \pi$  and  $(p_T^{jj})^2 = 0$ . The massive predictions are low in comparison to the data at low  $\Delta\phi^{jj}$  and high  $(p_T^{jj})^2$ . This discrepancy is enhanced for the resolved-enriched ( $x_\gamma^{\text{obs}} < 0.75$ ) sample. The HERWIG MC describes the shape of the measurements well. This indicates that either even higher-order calculations or a matching of the NLO matrix elements to a parton shower program (MC@NLO) are needed.

Jet shape variables in charm photoproduction ( $Q^2 < 1 \text{ GeV}^2$ ,  $0.2 < y < 0.8$ ) have been analysed by H1 [10]. An insight into the hard scatter process is possible due to the fact that the integrated jet shape  $\psi(r)$  is expected to be different for quark- and gluon-initiated jets. Jets were reconstructed with the  $k_T$  cluster algorithm. In the dijet sample ( $p_T^{\text{jet}_1(2)} > 7(6) \text{ GeV}$ ,  $|\eta| < 1.7$ ) one jet was tagged by a semileptonic decay muon

( $p_T^\mu > 2.5 \text{ GeV}$ ) as being initiated by a  $c$  quark using the two-dimensional fit of the muon transverse momentum with respect to the closest jet,  $p_T^{\text{rel}}$ , and the muon impact parameter,  $\delta$ , distributions to a mixture of ones in PYTHIA MC for light, charm and beauty quarks. The cut  $p_T^{\text{rel}} < 1 \text{ GeV}$  was imposed to get a charm enriched event sample. In Fig. 4 the average integrated jet shapes  $\langle \psi(r) \rangle$  are shown for the jet without the charm tag. For the resolved enriched sample ( $x_\gamma^{\text{obs}} \leq 0.75$ ) gluon jets are expected to dominate via the resolved photon charm excitation process,  $c_\gamma g \rightarrow c g$ , according to the PYTHIA MC predictions. This dominance is not observed in the data and on the contrary the integrated jet shape  $\langle \psi(r) \rangle$  is similar to one in the direct enriched sample ( $x_\gamma^{\text{obs}} > 0.75$ ) where quark jets are expected to dominate via the photon gluon process,  $\gamma g \rightarrow c\bar{c}$ .

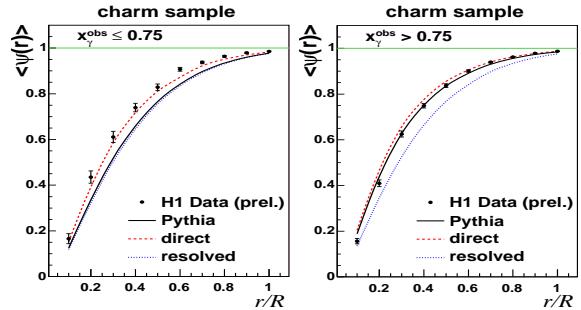


Figure 4. Average integrated jet shape for jets without charm tag for two different regions of  $x_\gamma^{\text{obs}}$  (resolved- and direct-enriched). The data are compared to PYTHIA MC predictions (total, direct and resolved contributions).

## 5. $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

The inclusive lifetime tagging technique have been used by H1 for the identification of heavy quark hadrons. The method is based on the track impact parameter,  $\delta$ , as measured by the H1 vertex detector. For heavy quarks tracks have high significance,  $S$ , defined as  $\delta$  divided by its error. Hence significance distributions  $S_i$  are considered where  $S_i$  is the significance of track with  $i$ -th highest absolute significance in an event. The  $c$ ,  $b$

and light quark fractions are extracted from the simultaneous fit to at least two distributions  $S_1$  and  $S_2$ . The method features low extrapolation factors (high acceptances).

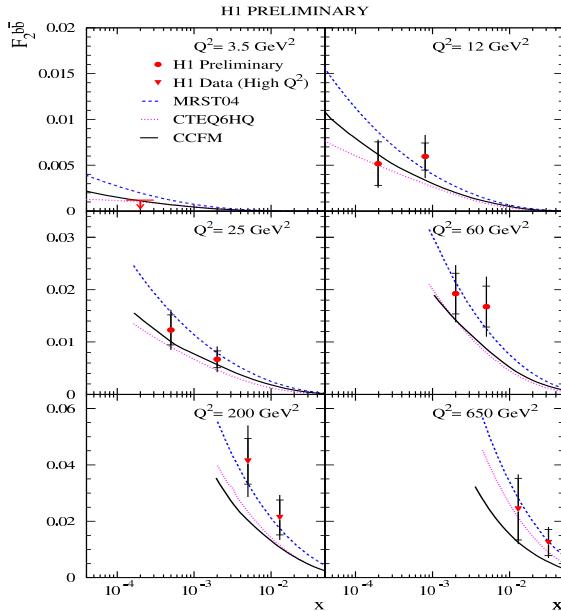


Figure 5. The structure function  $F_2^{b\bar{b}}$  as a function of  $x$  for different values of  $Q^2$ . The data are compared to NLO predictions in the framework of the VFNS (MRST, CTEQ) and predictions based on CCFM parton evolution.

The method allowed a purely inclusive measurement of charm and beauty dijet cross sections [11] as well as the first measurement of the beauty contribution in the structure function. Using three distributions  $S_1$ ,  $S_2$  and  $S_3$ , the measurement of  $F_2^{b\bar{b}}$  shown in Fig. 5 was extended to  $Q^2$  as low as  $Q^2 \leq 60 \text{ GeV}^2$  [12]. The data are described by the variable flavour number scheme (VFNS) NLO calculations. In the kinematic region of the measurement the beauty cross section is on average 0.8% of the total  $ep$  cross section (2.7% in the high- $Q^2$  measurement).

## 6. Beauty with dimuons

Specific topologies of events with  $B$  decays allow the identification of heavy quarks. Following the strategy of the previously done  $\mu-D^*$  cor-

relation analyses, the dimuon charge correlations and invariant mass distributions have been studied by ZEUS to measure beauty production [13]. Despite rather restricted statistics the analysis is sensitive to  $B$  mesons almost at rest due to low background and high acceptance down to low muon transverse momentum,  $p_T^\mu > 1.5 \text{ GeV}$ . The muon rapidity range,  $-2.2 < \eta^\mu < 2.5$ , is also wide due to almost full rapidity coverage of the muon detectors used in the analysis. The azimuthal separation of the the muons,  $\Delta\phi^{\mu\mu}$ , was measured for high dimuon invariant mass,  $m^{\mu\mu} > 3.25 \text{ GeV}$ , thus providing a direct probe of the  $b\bar{b}$  correlations. The total cross section measurement,  $\sigma_{\text{tot}}(ep \rightarrow b\bar{b}X) = 16.1 \pm 1.8(\text{stat.})^{+5.3}_{-4.8}(\text{syst.}) \text{ nb}$ , is to be compared to a NLO QCD prediction,  $6.8^{+3.0}_{-1.7} \text{ nb}$ .

## 7. Summary and outlook

The large data sample accumulated during HERA I running allowed H1 and ZEUS to test thoroughly different aspects of QCD in charm and beauty production processes. The NLO QCD calculations, where available, were found to be in general agreement with the data, although some measurements suggest that even more precision is needed. New results from the post-upgrade HERA II running with increased collision rates, polarised beams and upgraded detectors will bring more experimental precision in the heavy flavour studies.

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